

**APPLICATION FOR UNITED STATES PATENT****METHOD OF MANUFACTURING A SIDE STEM MONOPOLE ANTENNA**

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**INVENTORS**

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**CROSS REFERENCE TO RELATED APPLICATIONS**

The present application is based on, and claims priority from, U.S. Provisional Application No. 60/256,012, filed December 15, 2000.

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p. 17**FIELD OF THE INVENTION**

The present invention is directed to wireless voice and data communications, and more particularly to manufacturing a monopole antenna as a unitary piece.

**BACKGROUND**

An antenna is a device that transmits electrical signals into free space. The signals may be, for example, received by another antenna in a proximate or a distant location. A common antenna configuration is the well-known monopole antenna. A typical monopole consists of a straight wire mounted above and operating against a ground plane. A transmission arrangement such as a transmission line feeds electrical signals to the monopole with the ground plane serves as the ground potential for the transmission arrangement. An insulator is used to provide

electrical separation between the monopole and the ground plane. As is well known in the art, the ground plane provides a mirror image for the monopole mounted above it so that from the perspective of the antenna it is as if another monopole antenna is located below the ground plane. In this way, the ground plane and the monopole antenna mimic a dipole antenna arrangement.

- 5 For optimum performance of the monopole antenna at a particular frequency  $f$  of operation the length of the monopole antenna will be approximately one-quarter of the operating wavelength  $\lambda$  at that operating frequency  $f$ , or  $\lambda/4$ .

In general, for an antenna arrangement such as the typical monopole, the operating wavelength  $\lambda$  is related to the operating frequency  $f$  through the following relation:

$$\lambda = \frac{c}{f\sqrt{\epsilon_r}} \quad (1)$$

where  $c$  is the speed of light in vacuum and  $\epsilon_r$  is a relative permittivity associated with the insulator. Typically the operational frequency  $f$  is fixed by the application and the frequency limits design choices for the dimensional properties of the antenna.

- Minimization of the space taken up by components is often of paramount importance in the design of devices such as wireless computing and other portable devices. For high-frequency applications that require antennas mounted on printed circuit boards, a typical monopole antenna arrangement may be impractical because of the antenna lengths at the high frequencies. A common substrate used to construct printed circuit boards is FR4® board has a relative permittivity  $\epsilon_r$  of approximately 4.25. As an example of an antenna length at a high frequency, assuming that  $\epsilon_r \approx 1$ , at an exemplary frequency of 5.25 GHz ( $5.25 \times 10^9$  Hz) the operating wavelength within the FR4 substrate will be approximately 57 millimeters (mm) and the

corresponding  $\lambda/4$  length of the antenna will be approximately 14 mm. For some applications, antennas with comparable lengths simply consume too much space in the vertical direction relative to the ground plane so as to be prohibitive in terms of their use.

The need to decrease the length of antenna configurations relative to a ground plane has led to a number of antenna arrangements, particularly in instances where horizontal space is available relative the ground plane. One example is the inverted L antenna arrangement. The inverted L is essentially a typical monopole antenna that is bent at approximately 90 degrees. Typically, the total length of the inverted L antenna, including the bent portion, will be  $\lambda/4$ , however a significant portion of that length may be in the bent portion that is approximately parallel to the ground plane. This decreases the length of the antenna portion that protrudes in the vertical direction relative to the ground plane. In most practical cases, this length will be no less than  $\lambda/8$  due to the need to provide mechanical support for the bent portion of the antenna.

While this inverted L arrangement can achieve significant improvement in length reduction from the typical monopole antenna arrangement, better performance and length reduction can be achieved with the well-known top hat antenna. FIG. 1 is a diagram illustrating a side view of a traditional top hat antenna 100 mounted on a printed circuit board (PCB) 102. The top hat antenna 100 includes a disk or circular hat 104 of radius r and diameter d, and a cylindrical stem 106 of height h. Generally, the stem 106 and the circular hat 104 of the top hat antenna 100 are distinct pieces that are fused together via any of a series of well-known manufacturing processes to realize the top hat antenna 100. The top hat antenna 100 could also be machined from a single piece of metal. The PCB 102 includes a layer 108 of dielectric

material, a ground plane **110**, and a microstrip line or feed strip **112**. The thicknesses of the dielectric layer **108**, the ground plane **110**, and the feed strip **112** are exaggerated relative to the top hat antenna **100** and to one another for purposes of illustration. For example, the feed strip **112** and the ground plane **110** are typically microthin layers of metal, for example, copper. The feed strip **112** includes a contact area **114** and forms a microstrip with the ground plane **110** and the dielectric layer **108** to provide electrical signals to the top hat antenna **100** at the contact area **114** where the strip **112** contacts the stem **106**. Typically, the stem **106** of the top hat antenna **100** is soldered or otherwise fused to the feed strip **112** at the contact area **114**. The dielectric layer **108** insulates the top hat antenna **100** from the ground plane **110**. The top hat antenna **100** operates against the ground plane **108** to similarly mimic a dipole antenna effect.

The height  $h$  of the stem **106** together with the diameter  $d$  of the circular hat **104** are typically equal to one quarter of the operating wavelength  $\lambda$  at the operating frequency  $f$ , or  $\lambda/4$ . Typically, this implies that the height  $h$  of the stem **106** and thus the top hat antenna **100** approaches as low as  $\lambda/12$ . The top hat antenna **100** is an electrically small antenna, that is, the length of the antenna **100** is much smaller than the operating wavelength  $\lambda$ . In general, the performance of the traditional top hat antenna **100** at a particular operating frequency will vary according to the dimensions  $d$  and  $h$  of the antenna **100**. Overall, the top hat antenna **100** provides substantial savings in terms of height relative to the ground plane **110**.

One drawback of the traditional top hat antenna arrangement relates to mounting the top hat antenna on a PCB. The antenna is typically soldered or otherwise fused to the top of the PCB and to a microstrip line. Actually soldering the top hat antenna to the PCB is a complicated and

mechanically precarious procedure in and of itself. The shape of the top hat antenna requires that an operator or a machine apply the solder at a difficult angle. A traditional monopole antenna does not present the same degree of difficulty in soldering. Soldering either the monopole or the top hat antenna to the top side of the PCB, however, is a process step that might not otherwise be necessary on the top side of the PCB but for the mounting of antennas. Put another way, a top hat antenna or a monopole antenna might be the only element that requires soldering to the top side of the PCB.

It would be desirable to provide a structurally stable arrangement for mounting an antenna that eliminates a soldering process on the top side of a printed circuit board, and that alleviates many of the difficulties inherent in mounting certain types of antennas on the printed circuit board.

An additional drawback of the traditional top hat antenna arrangement relates to manufacturability of the antenna. While a traditional top hat antenna may be machined from a single piece of metal, the antenna is generally formed by soldering, or by otherwise fusing, two distinct pieces of material to each other, one piece representing the circular hat, for example, and one piece representing the stem, for example. A manufacturing process that serves to accomplish this soldering or fusing together of pieces will typically be somewhat complicated and prone to error because of the lengths and the sizes of the pieces involved. As a result, the process typically proves to be fairly expensive on a per element basis and may be quite costly to implement on a mass production basis.

It would be desirable to provide an antenna of minimal length, in terms of its height when positioned above a ground plane, that is less complicated and less expensive to manufacture than

a traditional top hat antenna but that does not significantly compromise performance relative to, for example, the traditional top hat antenna.

### SUMMARY

5           Methods of manufacturing antennas that are capable of being mounted on printed circuit boards are presented.

10           A method of manufacturing an antenna according to a presently preferred embodiment is presented in a first aspect of the present invention. The antenna is capable of being mounted on a printed circuit board. The design dimensions of a unitary piece of material are selected according to an operating wavelength. The unitary piece of material is stamped out from a larger section of material according to the design dimensions to form an antenna. The unitary piece includes a circular area and a stem area. The circular area has a center and an outer region. The stem area has a first end and a second end. The first end is joined with the outer region. The unitary piece is bendable at the first end and the outer region.

15           A method of manufacturing an antenna according to a presently preferred embodiment is presented in a second aspect of the present invention. The antenna is capable of being mounted on a printed circuit board. The design dimensions of a unitary piece of material are selected according to an operating wavelength. The unitary piece of material is stamped out from a larger section of material according to the design dimensions to form an antenna. The unitary piece includes a circular area, a stem area, and a foot area. The circular area has a center and an outer region. The stem area has a first end and a second end. The first end is joined with the outer region. The unitary piece is bendable at the first end and the outer region. The foot area has a

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third end and a fourth end. The third end is joined with the second end. The unitary piece is bendable at the third end and the second end.

A method of manufacturing an antenna according to a presently preferred embodiment is presented in a third aspect of the present invention. The antenna is capable of being mounted on a printed circuit board. The design dimensions of a unitary piece of material are selected according to an operating wavelength. The unitary piece of material is stamped out from a larger section of material according to the design dimensions to form an antenna. The unitary piece includes a circular area, a stem area, and a root area. The circular area has a center and an outer region. The stem area has a first end and a second end. The first end is joined with the outer region. The unitary piece is bendable at the first end and the outer region. The root area has a third end and a fourth end. The third end is joined with the second end. The second end has a first width and the third end has a second width. The first width exceeds the second width.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other features, aspects, and advantages will become more apparent from the following detailed description when read in conjunction with the following drawings, wherein:

FIG. 1 is a diagram illustrating a top hat antenna from the prior art;

FIG. 2 is a diagram illustrating a top view of an exemplary continuous, unitary piece of material used to form an exemplary side stem antenna according to a first presently preferred embodiment;

FIG. 3 is a diagram illustrating a three dimensional view of the exemplary unitary piece of material of FIG. 2 formed into the shape of the exemplary side stem antenna of FIG. 2;

FIG. 4 is a diagram illustrating a three dimensional view of the exemplary side stem antenna of FIGS. 2-3 mounted on a printed circuit board;

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FIG. 5 is a diagram illustrating a top view of an exemplary continuous, unitary piece of material used to form an exemplary side stem antenna according to a second presently preferred embodiment;

FIG. 6 is a diagram illustrating a three dimensional view of the exemplary unitary piece of material of FIG. 5 formed into the shape of the exemplary side stem antenna of FIG. 5;

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FIG. 7 is a diagram illustrating a three dimensional view of the exemplary side stem antenna of FIGS. 5-6 mounted on a printed circuit board;

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FIG. 8 is a diagram illustrating a top view of an exemplary continuous, unitary piece of material used to form an exemplary side stem antenna according to a third presently preferred embodiment;

FIG. 9 is a diagram illustrating a three dimensional view of the exemplary unitary piece of material of FIG. 5 formed into the shape of the exemplary side stem antenna of FIG. 8;

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FIG. 10 is a diagram illustrating a top view of an exemplary continuous, unitary piece of material used to form an exemplary central stem, or slotted hat, antenna according to a fourth presently preferred embodiment;

FIG. 11 is a diagram illustrating a three dimensional view of the exemplary unitary piece of material of FIG. 10 formed into the shape of the exemplary slotted hat antenna of FIG. 10;

FIG. 12 is a diagram illustrating a three dimensional view of the exemplary slotted hat antenna of FIGS. 10-11 mounted on a printed circuit board;

5<sup>th</sup> FIG. 13 is a diagram illustrating a top view of an exemplary continuous, unitary piece of material used to form an exemplary central stem, or slotted hat, antenna according to a fifth presently preferred embodiment;

FIG. 14 is a diagram illustrating a three dimensional view of the exemplary unitary piece of material of FIG. 13 formed into the shape of the exemplary slotted hat antenna of FIG. 13;

FIG. 15 is a diagram illustrating a three dimensional view of the exemplary slotted hat antenna of FIGS. 13-14 mounted on a printed circuit board;

10<sup>th</sup> FIG. 16 is a diagram illustrating a top view of an exemplary continuous, unitary piece of material used to form an exemplary central stem, or slotted hat, antenna according to a sixth presently preferred embodiment;

FIG. 17 is a diagram illustrating a three dimensional view of the exemplary unitary piece of material of FIG. 16 formed into the shape of the exemplary slotted hat antenna of FIG. 16;

15<sup>th</sup> FIG. 18 is a diagram illustrating a three dimensional view of an exemplary top hat antenna, according to a seventh presently preferred embodiment, mounted on a printed circuit board;

FIG. 19 is a diagram illustrating the exemplary top hat antenna of FIG. 18;

FIG. 20 is a diagram illustrating an exemplary portion of an exemplary antenna capable of being mounted on a printed circuit board in an exemplary mounting system shown in FIG. 27;

FIG. 21 is a diagram illustrating an exemplary portion of an exemplary antenna capable of being mounted on a printed circuit board in an exemplary mounting system shown in FIGS. 25-26;

FIG. 22 is a diagram illustrating a top view of an exemplary transmission feed according to FIG. 18.

FIG. 23 is a diagram illustrating a top view of an exemplary transmission feed according to FIG. 15.

FIG. 24 is a diagram illustrating a top view of an exemplary transmission feed according to FIG. 4.

FIG. 25 is a diagram illustrating a side view of an exemplary mounting system, built into a printed circuit board according to a eighth presently preferred embodiment, to mount the exemplary antenna of FIG. 21;

FIG. 26 is a diagram illustrating a bottom view of the exemplary mounting system of FIG. 25;

FIG. 27 is a diagram illustrating a side view of an exemplary mounting system, built into a printed circuit board according to an ninth presently preferred embodiment, to mount the exemplary antenna of FIG. 20;

FIG. 28 is a graph illustrating performance characteristics relating to input impedance for an exemplary implementation of the exemplary antenna of FIG. 4;

FIG. 29 is a graph illustrating performance characteristics relating to bandwidth for the exemplary implementation of the exemplary antenna of FIG. 4;

FIG. 30 is a magnified view of the graph of FIG. 29;

FIG. 31 is a graph illustrating performance characteristics relating to input impedance for an exemplary implementation of the exemplary antenna of FIG. 15;

FIG. 32 is a graph illustrating performance characteristics relating to bandwidth for the exemplary implementation of the exemplary antenna of FIG. 15;

5 FIG. 33 is a magnified view of the graph of FIG. 32;

FIG. 34 is a graph illustrating performance characteristics relating to input impedance for an exemplary implementation of the exemplary antenna of FIG. 18;

FIG. 35 is a magnified view of the graph of FIG. 34;

FIG. 36 is a graph illustrating performance characteristics relating to bandwidth for the exemplary implementation of the exemplary antenna of FIG. 18; and

FIG. 37 is a magnified view of the graph of FIG. 36.

#### DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

The present invention will now be described in detail with reference to the accompanying drawings, which are provided as illustrative examples of preferred embodiments of the present invention.

15 Copending U.S. Applications Serial No. \_\_\_/\_\_\_ filed on \_\_\_, 2000 and entitled METHOD AND SYSTEM FOR MOUNTING A MONOPOLE ANTENNA, and Serial No. \_\_\_/\_\_\_ filed on \_\_\_, 2000 and entitled METHOD OF MANUFACTURING A  
20 CENTRAL STEM MONOPOLE ANTENNA, and any divisional or continuation applications issuing therefrom, are hereby incorporated by reference herein.

*matu into patent  
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*this application*

Presented herein is a top-loaded monopole antenna according to a presently preferred exemplary embodiment, the stem of which is preferably formed by bending a rectangular stem area at a circular hat area of a unitary piece of material such that the stem area is perpendicular to the circular hat and remains joined with the hat at the perimeter, or more broadly, the outer region of the hat. Of course, the stem is not limited to a rectangular shape, and other shapes may be used as suitable. For example, the stem may be tapered to increase in width as it approaches the outer region of the circular hat. Since the stem of the antenna is joined with the hat at the outer region of the hat, the antenna may be referred to as an outer-stem, or side stem, antenna. The material used to construct the antenna may be, for example, a metal such as copper, although any suitable material, or combination of materials, may be used. In a preferred embodiment, the antenna is made out of one continuous stamped piece of flat metal.

The antenna may be mounted onto a PCB by inserting an area of the antenna identified as the root into a through-hole or, more broadly, an opening, on the PCB. In another embodiment, the antenna may be surface mounted onto the PCB by soldering or otherwise fusing an area of the antenna identified as the foot onto, for example, a microstrip line on the PCB. The foot area is preferably bent at the stem area such that the foot area is perpendicular to the stem area and remains joined with the stem area. The physical dimensions of the antenna, including those of the circular hat and the stem in the circular hat from which the stem was cut, are specifically designed to achieve optimum performance at the desired operating frequency. The antenna preferably allows for inexpensive manufacturing and easy mounting on a PCB, while preferably exhibiting desirable performance in this environment.

As an example, a side stem antenna according to a presently preferred embodiment was simulated using an antenna computer simulation program and was built as a prototype. The particular side stem antenna included a circular hat, a stem, and a foot. The foot was used for surface-mounting the antenna onto a PCB in a 50 Ohm microstrip feed system. The antenna of this presently preferred embodiment was designed to operate at a frequency of 5.25 GHz with a bandwidth of around 350 MHz at a voltage standing wave ratio (VSWR) of less than 2 and a bandwidth of around 600 MHz at a VSWR of less than 3. This exemplary antenna radiates omni-directionally in the mounting plane with vertical polarization and gain greater than 1 dB.

The side stem antenna may be used, for example, in any product that requires an antenna to be mounted on a PCB, specifically an antenna that preferably operates at a frequency of 2 GHz or above. Of course, it should be understood that the antenna is not limited to frequencies in the GHz range or higher. Neither is the antenna limited to PCB mounting environments. By adjusting the dimensions of the physical geometry of the antenna to fit a particular application, the antenna may be used with different parameters and in different environments.

The side stem antenna as described herein is a minimal length monopole antenna that is less complicated and less expensive to manufacture than a traditional top hat antenna. The side stem antenna is easy to manufacture, since the antenna is preferably stamped out as a unitary piece of continuous material and preferably requires limited manipulation, i.e., bending, to achieve a desired physical shape. The side stem antenna provides comparable performance relative to, for example, the traditional top hat antenna and can, through adjustment of its dimensions, be designed to operate at a wide variety of frequencies and in many environments.

### The Side Stem Antenna

Referring now to FIG. 2, it is a diagram illustrating a top view of an exemplary continuous, unitary piece of material **200** used to form an exemplary side stem antenna **200** according to a first presently preferred embodiment. The material **200** is illustrated prior to bending of the material **200** into a shape of the antenna **200**. The unitary piece of material **200** includes a circular hat area or hat **202**, a stem area or stem **204**, and a foot area or foot **206**. The circular hat area **202** includes a center **218** and an outer region **220** that extends along the portion of the perimeter of the material **200** that includes the circular hat area **202**. The dimensional parameters of the antenna **200** include a diameter  $d_h$  of the hat **202**, a radius  $r_h$  of the hat **202** that is preferably defined, for example, from the center **218** to a point **224** on the outer region **220** along a radial axis **222**, a width  $w_s$  of the stem **204**, a width  $w_f$  of the foot **206**, a length  $l_s$  of the stem **204**, and a length  $l_f$  of the foot **206**. In a preferred embodiment, the length  $l_f$  of the foot **206** is equivalent to the width  $w_s$  of the stem **204** and to the width  $w_f$  of the foot **206**, although the relative dimensions of the antenna **200** may vary as suitable according to the particular application in which the antenna **200** is used.

The dotted lines **226**, **228** in FIG. 2 are included for purposes of illustration to indicate the various areas **202**, **204**, **206** and to identify desired lines at which the unitary piece of material **200** is bendable, or may be bent, to form the side stem antenna **200**. The material **200** may contain an impression or a ridge along a desired bending line, such as that identified by the dotted lines in FIG. 2, that aids in bending the material **200** into the shape of the antenna **200**. The length  $l_s$  of the stem **204** is defined between the dotted lines **226**, **228**. The stem **204** is joined with the outer region **220** of the circular hat **202** at the dotted line **226**. The stem **204**

protrudes outward from the outer region **220** along the radial axis **222**. The unitary piece of material **200** is bendable, and thus an angle between the hat **202** and the stem **204** is adjustable, at the dotted line **226**. The length  $l_f$  of the foot **206** is defined between the dotted line **228** and an end **230** of the foot area **202** and of the material **200**. The foot **206** is joined with the stem **204** at the dotted line **228**. The unitary piece of material **200** is bendable, and thus an angle between the stem **204** and the foot **206** is adjustable, at the dotted line **228**.

FIG. 3 is a diagram illustrating a three dimensional view of the exemplary unitary piece of material **200**, formed into the shape of the exemplary side stem antenna **200**. The dimensional parameters of the antenna **200** further include a thickness  $t_h$  of the circular hat **202**, a thickness  $t_s$  of the stem **204**, and a thickness  $t_f$  of the foot **206**. In general, the unitary piece of material **200**, and thus the side stem antenna **200**, will have uniform thickness throughout the hat **202**, stem **204**, and foot **206** areas, although, of course, other thicknesses are possible. In a preferred embodiment, the material **200** is a metal material, such as copper, although any suitable conductive material may be used as suitable. The material **200** is preferably stamped out in the shape illustrated in FIG. 2 from a larger planar, flat, continuous, piece of material in a manufacturing process. Preferably, the material **200** is stamped out in accordance with the design dimensions of the side stem antenna **200**. Any cutting or stamping process may be used as suitable to stamp out the material **200** from the larger piece. The larger piece of material will typically be available in standard widths from material manufacturers and a standard width may be chosen, for example, for mechanical stability purposes, for durability, or for bendability.

In FIG. 3, the unitary piece of material **200** is bent into a shape capable of operating as an antenna. As shown in FIG. 3, preferably the unitary piece of material **200** is bent so that the hat

202 and the stem 204 are perpendicular to one another. Of course, the angle between the hat 202 and the stem 204 is variable and may be adjusted as suitable for performance or mechanical stability reasons, for example. Preferably the unitary piece 200 is bent so that the stem 204 and the foot 206 are perpendicular to one another. Of course, the angle between the stem 204 and the foot 206 is variable and may be adjusted as suitable for performance or mechanical stability reasons, for example.

Preferably, the design dimensions of the antenna 200 are selected in accordance with the environment within which the antenna is intended to operate. For example, in a preferred embodiment, the design dimensions are selected according to an operating frequency, and a corresponding operating wavelength, or corresponding ranges of these, for the antenna 200.

Although selection of the design dimensions is a matter of design choice, as a designer must determine the relative importance of different performance criteria, some rules of thumb may accompany design intuition and numerical modeling of the design dimensions. For example, in a preferred embodiment, the desired length  $l_s$  of the stem 204 of the side stem antenna 200 is approximately one-tenth to one-twelfth of the operating wavelength, or from  $\lambda/10$  to  $\lambda/12$ , in the interest of minimizing the height of the antenna 200 above, for example, a PCB.

Preferably, the height of the antenna 200 above the PCB is roughly equivalent to the length  $l_s$  of the stem 204. A design rule of thumb to achieve the length  $l_s$  and to maintain acceptable performance that is comparable to the traditional top hat antenna 100 illustrated in FIG. 1, is to make the radius  $r_h$  of the hat 202 approximately equivalent to the length  $l_s$  of the stem 204 so that:

$$d_h = 2r_h \approx 2l_s \quad (2)$$

and

$$d_h + l_s = 2r_h + l_s \approx \frac{\lambda}{4} \quad (3)$$

where, as above,  $d_h$  is the diameter of the hat **204**. In a preferred embodiment, the radius  $r_h$  of the hat and the length  $l_s$  of the stem are selected to satisfy (3) and to minimize  $l_s$ . For example, if the length  $l_s$  is selected to be approximately equal to  $\lambda/12$ , then according to (3) the radius  $r_h$  should be approximately equal to  $\lambda/12$ . As another example, if the length  $l_s$  is selected to be approximately equal to  $\lambda/10$ , then to satisfy (3) the radius  $r_h$  should be approximately equal to  $\lambda/13$ .

The antenna **200** is capable of being mounted on a printed circuit board (PCB), as shown in FIG. 4. The antenna **200** of FIG. 4 is mounted on a PCB **208** and contacts a transmission feed **216** that is laid out along the top side of the PCB **208**. The PCB **208** includes, for example, a substrate such as FR4® board, although other dielectric materials may be used as suitable. FIG. 24 is a diagram illustrating a top view of the exemplary transmission feed **216** of FIG. 4 without the antenna **200**. The transmission feed **216** preferably includes a microstrip line **214**, a taper region **212**, and a contact area or connecting pad **210**. Preferably, the transmission feed **216** is a microthin layer of metal film, such as copper, although other metals and conductive materials may be used as suitable.

As can be seen from FIG. 4, the purpose of the foot **206** of the antenna **200** is to mount the antenna **200** on a surface, such as the PCB **208**. Preferably, a process is used to solder, or

otherwise fuse, the foot 206 of the antenna 200 to the PCB 208. The width  $w_f$  and the length  $l_f$  of the foot 206 are critical for mechanical stability of the antenna 200. The dimensions are preferably carefully selected using mechanical intuition and numerical simulation so that the foot 206 is long enough and so that the foot 206, and the stem 204 at its end nearest the foot 206, are wide enough to mechanically support the antenna 200 and maintain the antenna 200 in the position illustrated in FIG. 4, i.e., so that the hat 202 is parallel to the PCB 208. For example, if the length  $l_f$  of the foot 206 is too short relative to the rest of the antenna 200, and provides no counterbalance to the stem 204 and the hat 206, the foot 206 may peel off from the connecting pad 210. Similarly, if the width  $w_f$  of the foot 206 and the width  $w_s$  of the stem is too thin relative to the hat, the antenna 200 may not be supported effectively, and may be prone to undesired bending or breaking.

The width  $w_f$  of the foot 206, in turn, determines the width  $w_p$  of the connecting pad 210 and the width of the taper region 212 where the taper region 212 joins with the connecting pad 210. The connecting pad 210 is preferably used to make electrical contact with the foot 206 and thus the antenna 200, and to provide a surface onto which the foot 206 and the antenna 200 may be soldered. The microstrip line 214, as is commonly known in the art, is a structure that behaves like a transmission line at microwave frequencies and that transmits electrical signals in conjunction with a dielectric layer and a ground plane, in this case with the PCB 208. For a given width, such as width  $w_m$ , of microstrip line and a given height of the microstrip line above a ground plane, typically the thickness of the PCB layer, there is an impedance associated with the microstrip line. Preferably, the taper region 212 is used to match the input impedance of the antenna 200 with the microstrip line 214. The length  $l_t$  of the taper region 212 is dependent on

how abrupt a transformation of the microstrip line **214** to the connecting pad **210** is acceptable for a particular application. The tradeoff for this parameter is between reducing the length  $l_{\text{feed}}$  of the transmission feed **216** to save area on the PCB **208** and avoiding unwanted reflections that can result from a more abrupt transformation from the width  $w_m$  of the microstrip line **214** to the width  $w_p$  of the connecting pad **210**. The length  $l_p$  of the connecting pad **210** preferably is determined according to the length  $l_f$  of the foot **206**.

Table I shows the results of a computer simulation run using a standard antenna design simulation software package, as well as the assumed values for various dimensions of an exemplary side stem antenna **200** implemented as in FIG. 4. The values for the dimensions of the exemplary side stem antenna **200** were obtained through iterative optimization using the software package. An exemplary prototype implementation of the side stem antenna **200** of FIG. 4 utilizes FR4® board as the dielectric material for the PCB **208**.

**Table I**

**Simulation results for an exemplary implementation of the exemplary side stem antenna 200 with foot 206 of FIG. 4; including dimensions of the exemplary transmission feed 216 of FIGS. 4 and 24.**

Element/Dimension	Value
Operating Frequency	5.25 GHz
Material <b>200</b> Thickness $t_h$ , $t_s$ , $t_f$	0.2 mm
Diameter of Hat <b>202</b> $d_h$ ; $2r_h$	8.432 mm

Length of Stem <b>204</b> $l_s$ , $\approx$ Height above PCB <b>208</b>	4.22 mm $[d_h = 2r_h \approx 2l_s; d_h + l_s = 2r_h + l_s \approx \frac{\lambda}{4}]$
Width of Stem <b>204</b> $w_s$ ; Width of Foot <b>206</b> $w_f$	1.69 mm
Length of Foot <b>206</b> $l_f$	1.69 mm
Length of Transmission Feed <b>216</b>	8.96 mm $[l_{feed} = l_p + l_t + l_m]$
Thickness of Transmission Feed <b>216</b>	0.07 mm (70 $\mu$ m)
Impedance of Microstrip Line <b>214</b>	50 $\Omega$
Width of Microstrip Line <b>214</b> $w_m$	0.45 mm
Length of Microstrip Line <b>214</b> $l_m$	4.76 mm
Length of Taper Region <b>212</b> $l_t$	1.9 mm
Width of Connecting Pad <b>210</b> $w_p$	2.3 mm
Length of Connecting Pad <b>210</b> $l_p$	2.3 mm
FR4® board (PCB <b>208</b> )	$\epsilon_R \approx 4.25$

FIGS. 28-30 are graphs illustrating performance characteristics relating to input impedance and the bandwidth according to the exemplary implementation of the exemplary side stem antenna **200** of FIG. 4. In FIG. 28, the real and imaginary parts of the input impedance, in units of Ohms ( $\Omega$ ), of the antenna **200** on the vertical scale are plotted against frequency, in unit of GHz, on the horizontal scale. At the operating frequency  $f$  of 5.25 GHz, the real part of the

input impedance is approximately  $50\ \Omega$ , so that the microstrip line **214** of the transmission feed **216**, which has an impedance of  $50\ \Omega$  as shown in Table I, is effectively matched by the antenna **200**. In FIG. 29 the bandwidth of the antenna is shown with the magnitude of the voltage standing wave ratio (VSWR) plotted on the vertical scale against frequency on the horizontal scale. The bandwidth for a VSWR less than 3 is around 600 MHz, between 4.9 GHz and 5.5 GHz. FIG. 30 is a magnified portion of the graph in FIG. 29, focused so that the bandwidth for a VSWR less than 2 can more easily be discerned. The bandwidth for  $\text{VSWR} < 2$  is around 370 MHz, between 5.05 GHz and 5.42 GHz. In a neighborhood of the operating frequency  $f = 5.25\text{GHz}$ , the bandwidths are comparable to the bandwidths associated with a traditional top hat antenna, such as the top hat antenna **100** of FIG. 1.

Referring now to FIG. 5, it is a diagram illustrating a top view of an exemplary continuous, unitary piece of material **300** used to form an exemplary side stem antenna **300** according to a second presently preferred embodiment. As will be evident from inspection of FIG. 5, the antenna **300** is similar in nature to the antenna **200** and the description of the antenna **200** with regard to FIGS. 2-4, subject to the following additional commentary, will provide sufficient instruction to one skilled in the art. The exemplary side stem antenna **300** differs from the antenna **200** in that the material **300** used to form the antenna **300** includes a root area or root **306** rather than a foot area or foot **206**. The root **306** has a length  $l_r$  measured from an end **328** of a stem area or stem **304**, at which the root **306** is joined to the stem **304**, to an end **330** of the root **306**. The root **306** has a width  $w_r$  that, by definition of this embodiment, is preferably less than a width  $w_s$  of the stem **304**. That is, the width  $w_s$  preferably exceeds the width  $w_r$ .

In FIG. 6, the unitary piece of material 300 is bent into a shape capable of operating as an antenna. As shown in FIG. 6, preferably the unitary piece of material 300 is bent so that a hat area or hat 302 and the stem 304 are perpendicular to one another. Of course, the angle between the hat 302 and the stem 304 is variable and may be adjusted as suitable for performance or mechanical stability reasons, for example. Depending on the nature of the material 300 and a thickness  $t_s$ ,  $t_h$ ,  $t_r$  of the material 300 that is used for the antenna 300, the root 304 may be bendable. However, by definition of this exemplary embodiment, the root 304 preferably does not bend at the end 328 at which the root 306 is joined to the stem 304, but rather remains flat and in the same plane as with the stem 304 as illustrated in FIG. 6.

FIG. 7 is a diagram illustrating a three dimensional view of the exemplary side stem antenna 300 of FIGS. 5-6 mounted on a PCB 308. The PCB 308 includes, for example, a substrate such as FR4® board, although other dielectric materials may be used as suitable. The stem 304 is preferably wider than the root 306 and the root 306 preferably lies in the same plane as the stem 304 for reasons that will become evident when viewing the antenna 300 of FIG. 7 and when reviewing the description below of mounting systems according to presently preferred embodiments. In FIG. 7, for example, the stem 304 is supported by a transmission feed 316 that is laid out along a top side of the PCB 308, while the root 304 penetrates the PCB 308 through to a bottom side of the PCB 308. The transmission feed 316 preferably includes a microstrip line 314, a taper region 312 and a connecting pad 310. Preferably, the transmission feed 316 is a microthin layer of metal film, such as copper, although other metals and conductive materials may be used as suitable. The connecting pad 310 is preferably semi-circular having a radius  $r_p$  and is joined with the taper region 312. The connecting pad 310 may also be defined as a circle

so that the taper region 312 and the connecting pad 310 overlap in terms of area. The root 304 and thus the antenna 300 are preferably secured to the PCB 308 by a process that solders or otherwise fuses the root 304 to the bottom of the PCB 308 as explained in more detail below with regard to FIGS. 15, 23, 20, and 27.

5 Referring now to FIG. 8, it is a diagram illustrating a top view of an exemplary continuous, unitary piece of material 400 used to form an exemplary side stem antenna 400 according to a third presently preferred embodiment. As will be evident from inspection of FIG. 8, the antenna 400 is similar in nature to the antenna 200 and the description of the antenna 200 with regard to FIGS. 2-4, subject to the following additional commentary, will provide sufficient instruction to one skilled in the art. The exemplary side stem antenna 400 differs from the antenna 200 in that the material 400 used to form the antenna 400 includes a stem area or stem 404 that is gradually tapered from a first width  $w_{s1}$  at a dotted line 426 at which the stem 404 is joined with a hat area or hat 402, to a second width  $w_{s2}$  at a dotted line 428 at which the stem 404 is joined with a foot area or foot 406. The foot 406 has a width  $w_f$  that, by definition of this 15 embodiment, is preferably less than the width  $w_{s1}$  of the stem 404. and is preferably equal to the width  $w_{s2}$  of the stem 404. Therefore, the width  $w_{s1}$  preferably exceeds the widths  $w_{s2}$  and  $w_f$ . In some embodiments, simulations on exemplary side stem antennas mounted on printed circuit boards with a similarly tapered stem showed performance improvements with regard to bandwidth. The tapered stem in a PCB mounting environment exploits the electric field that 20 expands gradually alongside from the base of the tapered stem closest to the PCB to the top of the stem at the hat of the side stem antenna.

In FIG. 9, the unitary piece of material 400 is bent into a shape capable of operating as an antenna. As shown in FIG. 9, preferably the unitary piece of material 400 is bent so that the hat 402 and the stem 404 are perpendicular to one another. Of course, the angle between the hat 402 and the stem 404 is variable and may be adjusted as suitable for performance or mechanical stability reasons, for example. Preferably the unitary piece 400 is bent so that the stem 404 and the foot 406 are perpendicular to one another. Of course, the angle between the stem 404 and the foot 406 is variable and may be adjusted as suitable for performance or mechanical stability reasons, for example.

#### **The Central Stem, or Slotted Hat Antenna**

Referring now to FIG. 10, it is a diagram illustrating a top view of an exemplary continuous, unitary piece of material 500 used to form an exemplary central stem, or slotted hat, antenna 500 according to a fourth presently preferred embodiment. The material 500 is illustrated prior to bending of the material 500 into a shape of the antenna 500. The unitary piece of material 500 includes a circular hat area or hat 502, a stem area or stem 504, and a foot area or foot 506. The circular hat area 502 includes a center 518 and an outer region 520 that extends along the portion of the perimeter of the material 500 that includes the circular hat area 502. The dimensional parameters of the antenna 500 include a diameter  $d_h$  of the hat 502, a radius  $r_h$  of the hat 502 that is preferably defined, for example, from the center 518 to a point 524 on the outer region 520 along a radial axis 522, a width  $w_s$  of the stem 504, a width  $w_f$  of the foot 506, a length  $l_s$  of the stem 504, and a length  $l_f$  of the foot 506. In a preferred embodiment, the length  $l_f$  of the foot 506 is equivalent to the width  $w_s$  of the stem 504 and to the width  $w_f$  of the foot 506,

although the relative dimensions of the antenna **500** may vary as suitable according to the particular application in which the antenna **500** is used.

The dotted lines **526**, **528** in FIG. 10 are included for purposes of illustration to indicate the various areas **502**, **504**, **506** and to identify desired lines at which the unitary piece of material **500** is bendable, or may be bent, to form the slotted hat antenna **500**. The material **500** may contain an impression or a ridge along a desired bending line, such as that identified by the dotted lines in FIG. 10, that aids in bending the material **500** into the shape of the antenna **500**.

The length  $l_s$  of the stem **504** is defined between the dotted lines **526**, **528**. The stem **504** has a first side **532** and a second side **534**. Preferably, the sides **532**, **534** are defined by a process that stamps or cuts the stem **504** out of the circular hat **502** along the first side **532** and the second side **534**. The stem **504** is joined with the center **518** of the circular hat **502** at the dotted line **526**. Following the process of stamping or cutting, the stem **504** preferably remains joined with the center **518** of the hat **502** along the dotted line **526**. The stem **504** protrudes outward from the center **518** along the radial axis **522**. The unitary piece of material **500** is bendable, and thus an angle between the hat **502** and the stem **504** is adjustable, at the dotted line **526**, so that when the stem **504** is bent, a rectangular slot **536** is left in the hat **502**. The length  $l_f$  of the foot **506** is defined between the dotted line **528** and an end **530** of the foot area **502** and of the material **500**. The foot **506** is joined with the stem **504** at the dotted line **528**. The unitary piece of material **500** is bendable, and thus an angle between the stem **504** and the foot **506** is adjustable, at the dotted line **528**.

FIG. 11 is a diagram illustrating a three dimensional view of the exemplary unitary piece of material **500**, formed into the shape of the exemplary slotted hat antenna **500**. The

dimensional parameters of the antenna **500** further include a thickness  $t_h$  of the circular hat **502**, a thickness  $t_s$  of the stem **504**, and a thickness  $t_f$  of the foot **506**. In general, the unitary piece of material **500**, and thus the slotted hat antenna **500**, will have uniform thickness throughout the hat **502**, stem **504**, and foot **506** areas, although, of course, other thicknesses are possible. In a preferred embodiment, the material **500** is a metal material, such as copper, although any suitable conductive material may be used as suitable. The material **500** is preferably stamped out in the shape illustrated in FIG. 10 from a larger planar, flat, continuous, piece of material in a manufacturing process. Preferably, the material **500** is stamped out in accordance with the design dimensions of the slotted hat antenna **500**. Any cutting or stamping process may be used as suitable to stamp out the material **500** from the larger piece. The larger piece of material will typically be available in standard widths from material manufacturers and a standard width may be chosen, for example, for mechanical stability purposes, for durability, or for bendability.

In FIG. 11, the unitary piece of material **500** is bent into a shape capable of operating as an antenna. As shown in FIG. 11, preferably the unitary piece of material **500** is bent so that the hat **502** and the stem **504** are perpendicular to one another, leaving the rectangular slot **536** in the hat **502**. Of course, the angle between the hat **502** and the stem **504** is variable and may be adjusted as suitable for performance or mechanical stability reasons, for example. Preferably the unitary piece **500** is bent so that the stem **504** and the foot **506** are perpendicular to one another. Of course, the angle between the stem **504** and the foot **506** is variable and may be adjusted as suitable for performance or mechanical stability reasons, for example.

Preferably, the design dimensions of the antenna **500** are selected in accordance with the environment within which the antenna is intended to operate. For example, in a preferred

embodiment, the design dimensions are selected according to an operating frequency, and a corresponding operating wavelength, or corresponding ranges of these, for the antenna 500.

Although selection of the design dimensions is a matter of design choice, as a designer must determine the relative importance of different performance criteria, some rules of thumb may accompany design intuition and numerical modeling of the design dimensions. For example, in a preferred embodiment, the desired length  $l_s$  of the stem 504 of the slotted hat antenna 500 is approximately one-tenth to one-twelfth of the operating wavelength, or from  $\lambda/10$  to  $\lambda/12$ , in the interest of minimizing the height of the antenna 500 above, for example, a PCB. Preferably, the height of the antenna 500 above the PCB is roughly equivalent to the length  $l_s$  of the stem 504. A design rule of thumb to achieve the length  $l_s$  and to maintain acceptable performance that is comparable to the traditional top hat antenna 100 illustrated in FIG. 1, is to make the radius  $r_h$  of the hat 502 approximately equivalent to the length  $l_s$  of the stem 504 so that (2) and (3) above are satisfied. In a preferred embodiment, the radius  $r_h$  of the hat and the length  $l_s$  of the stem are selected to satisfy (3) and to minimize  $l_s$ . For example, if the length  $l_s$  is selected to be approximately equal to  $\lambda/12$ , then according to (3) the radius  $r_h$  should be approximately equal to  $\lambda/12$ . As another example, if the length  $l_s$  is selected to be approximately equal to  $\lambda/10$ , then to satisfy (3) the radius  $r_h$  should be approximately equal to  $\lambda/13$ .

The antenna 500 is capable of being mounted on a printed circuit board (PCB), as shown in FIG. 12. The antenna 500 of FIG. 12 is mounted on a PCB 508 and contacts a transmission

feed **516** that is laid out along the top side of the PCB **508**. The PCB **508** includes, for example, a substrate such as FR4® board, although other dielectric materials may be used as suitable. The transmission feed **516** preferably includes a microstrip line **514**, a taper region **512**, and a contact area or connecting pad **510**. Preferably, the transmission feed **516** is a microthin layer of metal film, such as copper, although other metals and conductive materials may be used as suitable. FIG. 24 is a diagram illustrating a top view of the exemplary transmission feed **216** of FIG. 4 without the antenna **200**. The exemplary transmission feed **216** is analogous to the exemplary transmission feed **516**.

As can be seen from FIG. 12, the purpose of the foot **506** of the antenna **500** is to mount the antenna **500** on a surface, such as the PCB **508**. Preferably, a process is used to solder, or otherwise fuse, the foot **506** of the antenna **500** to the PCB **508**. The width  $w_f$  and the length  $l_f$  of the foot **506** are critical for mechanical stability of the antenna **500**. The dimensions are preferably carefully selected using mechanical intuition and numerical simulation so that the foot **506** is long enough and the foot **506**, and the stem **504** at its end nearest the foot **506**, are wide enough to mechanically support the antenna **500** and maintain the antenna **500** in the position illustrated in FIG. 12, i.e., so that the hat **502** is parallel to the PCB **508**. For example, if the length  $l_f$  of the foot **506** is too short relative to the rest of the antenna **500**, and provides no counterbalance to the stem **504** and the hat **502**, the foot **506** may peel off from the connecting pad **510**. Similarly, if the width  $w_f$  of the foot **506** and the width  $w_s$  of the stem is too thin relative to the hat, the antenna **500** may not be supported effectively, and may be prone to undesired bending or breaking.

15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120 125 130 135 140 145 150 155 160 165 170 175 180 185 190 195 200 205 210 215 220 225 230 235 240 245 250 255 260 265 270 275 280 285 290 295 300 305 310 315 320 325 330 335 340 345 350 355 360 365 370 375 380 385 390 395 400 405 410 415 420 425 430 435 440 445 450 455 460 465 470 475 480 485 490 495 500 505 510 515 520 525 530 535 540 545 550 555 560 565 570 575 580 585 590 595 600 605 610 615 620 625 630 635 640 645 650 655 660 665 670 675 680 685 690 695 700 705 710 715 720 725 730 735 740 745 750 755 760 765 770 775 780 785 790 795 800 805 810 815 820 825 830 835 840 845 850 855 860 865 870 875 880 885 890 895 900 905 910 915 920 925 930 935 940 945 950 955 960 965 970 975 980 985 990 995

The width  $w_f$  of the foot **506**, in turn, determines the width of the connecting pad **510** and the width of the taper region **512** where the taper region **512** joins with the connecting pad **510**. The connecting pad **510** is preferably used to make electrical contact with the foot **506** and thus the antenna **500**, and to provide a surface onto which the foot **506** and the antenna **500** may be soldered. The microstrip line **514**, as is commonly known in the art, is a structure that behaves like a transmission line at microwave frequencies and that transmits electrical signals in conjunction with a dielectric layer and a ground plane, in this case with the PCB **508**. For a given width, such as width  $w_m$ , of microstrip line and a given height of the microstrip line above a ground plane, typically the thickness of the PCB layer, there is an impedance associated with the microstrip line. Preferably, the taper region **512** is used to match the input impedance of the antenna **500** with the microstrip line **514**. The length of the taper region **512** is dependent on how abrupt a transformation of the microstrip line **514** to the connecting pad **510** is acceptable for a particular application. The tradeoff for this parameter is between reducing the length of the transmission feed **516** to save area on the PCB **508** and avoiding unwanted reflections that can result from a more abrupt transformation along the taper region **512** from the width of the microstrip line **514** to the width of the connecting pad **510**. The length of the connecting pad **510** preferably is determined according to the length of the foot **506**.

The rectangular slot **536** in the circular hat **502** has implications for the performance of the slotted hat antenna **500**. The current in a typical top hat antenna, such as the traditional top hat antenna **100** of FIG. 1 spreads radially outward in all directions equally over the circular hat **104**. If the rectangular slot **536** of material is removed from the circular hat **502**, there is a higher concentration of current around the slot **536**. So the slot width, that is, the width  $w_s$  of the stem

504, is one of the parameters that must be selected with care. If too much width  $w_s$  is selected for the stem 504, the rectangular slot 536 in the hat 502 will be too wide and the resulting antenna 500 will suffer from a lack of rotational symmetry. In general, the narrower the stem 504, the narrower the slot 536, and the better the performance of the antenna 500. If too small a width  $w_s$  is selected for the stem 504, the antenna 500 will be less stable mechanically. In addition, a mass production process that utilizes current technology to manufacture the antenna 500, the process of stamping out, or cutting, the stem 504 along the sides 532, 534 is problematic. The smaller the width  $w_s$  of the stem 504 that is sought in production, the more likely that errors will occur, such as the stem 504 being inadvertently cut off. Since the stem 504 is not discarded from the stamping out or cutting process, but rather is used in the antenna 500, the width  $w_s$  is a critical parameter that is limited by the process in question. A rule of thumb for selecting the stem 504 width  $w_s$  in the antenna 500 is to attempt to select the minimum stem 504 width  $w_s$ , for performance purposes, that provides both mechanical stability and support for the antenna 500 and that provides enough margin of error for current stamping out and cutting processes.

Referring now to FIG. 13, it is a diagram illustrating a top view of an exemplary continuous, unitary piece of material 600 used to form an exemplary slotted hat antenna 600 according to a fifth presently preferred embodiment. As will be evident from inspection of FIG. 5, the antenna 600 is similar in nature to the antenna 500 and the description of the antenna 500 with regard to FIGS. 10-12, subject to the following additional commentary, will provide sufficient instruction to one skilled in the art. The exemplary slotted hat antenna 600 differs from the antenna 500 in that the material 600 used to form the antenna 600 includes a root area

or root 606 rather than a foot area or foot 506. The root 606 has a length  $l_r$  measured from an end 628 of a stem area or stem 604, at which the root 606 is joined to the stem 604, to an end 630 of the root 606. The root 606 has a width  $w_r$  that, by definition of this embodiment, is preferably less than a width  $w_s$  of the stem 604. That is, the width  $w_s$  preferably exceeds the width  $w_r$ .

5 In FIG. 14, the unitary piece of material 600 is bent into a shape capable of operating as an antenna. As shown in FIG. 14, preferably the unitary piece of material 600 is bent so that a hat area or hat 602 and the stem 604 are perpendicular to one another. Of course, the angle between the hat 602 and the stem 604 is variable and may be adjusted as suitable for performance or mechanical stability reasons, for example. Depending on the nature of the material 600 and a thickness  $t_s$ ,  $t_h$ ,  $t_r$  of the material 600 that is used for the antenna 600, the root 604 may be bendable. However, by definition of this exemplary embodiment, the root 604 preferably does not bend at the end 628 at which the root 606 is joined to the stem 604, but rather remains flat and in the same plane as with the stem 604 as illustrated in FIG. 14.

FIG. 15 is a diagram illustrating a three dimensional view of the exemplary slotted hat antenna 600 of FIGS. 13-14 mounted on a PCB 608. The PCB 608 includes, for example, a substrate such as FR4® board, although other dielectric materials may be used as suitable. The stem 604 is preferably wider than the root 606 and the root 606 preferably lies in the same plane as the stem 604 for reasons that will become evident when viewing the antenna 600 of FIG. 15 and when reviewing the description below of mounting systems according to presently preferred  
20 embodiments. In FIG. 15, for example, the stem 604 is supported by a transmission feed 616 that is laid out along a top side of the PCB 608, while the root 604 penetrates the PCB 608 through to a bottom side of the PCB 608. The transmission feed 616 preferably includes a

microstrip line 614, a taper region 612 and a contact area or connecting pad 610. Preferably, the transmission feed 616 is a microthin layer of metal film, such as copper, although other metals and conductive materials may be used as suitable. FIG. 23 is a diagram illustrating a top view of the exemplary transmission feed 616 without the antenna 600. The exemplary transmission feed 616 is also analogous to the exemplary transmission feed 316. The connecting pad 610 of FIGS. 15, 23 is preferably semi-circular having a radius  $r_p$  and is joined with the taper region 612. The connecting pad 610 may also be defined as a circle so that the taper region 612 and the connecting pad 610 overlap in terms of area. The root 604 and thus the antenna 600 are preferably secured to the PCB 608 by a process that solders or otherwise fuses the root 604 to the bottom of the PCB 608 as explained in more detail below.

The width  $w_r$  of the root 606 and preferably the width  $w_s$  of the stem 604 determine the radius  $r_p$  and the diameter  $d_p$  of the connecting pad 610 and the width of the taper region 612 where the taper region 612 joins with the connecting pad 610. The connecting pad 610 is preferably used to make electrical contact with the root 606 and thus the antenna 600, and to provide a surface to support the stem 604 and thus the antenna 600. Preferably, the root 606 penetrates the connecting pad 610 through a pad hole 638. Preferably, the pad hole 638 is shaped to firmly and tightly surround the root 606 to facilitate the electrical contact between the connecting pad 610 and the root 606. The width  $w_{\text{phole}}$  of the pad hole 638 is preferably equivalent to the width  $w_r$  of the root 606. The microstrip line 614, as is commonly known in the art, is a structure that behaves like a transmission line at microwave frequencies and that transmits electrical signals in conjunction with a dielectric layer and a ground plane, in this case with the PCB 608. For a given width, such as width  $w_m$ , of microstrip line and a given height of

the microstrip line above a ground plane, typically the thickness of the PCB layer, there is an impedance associated with the microstrip line. Preferably, the taper region 612 is used to match the input impedance of the antenna 600 with the microstrip line 614. The length  $l_t$  of the taper region 612 is dependent on how abrupt a transformation of the microstrip line 614 to the connecting pad 610 is acceptable for a particular application. The tradeoff for this parameter is between reducing the length  $l_{\text{feed}}$  of the transmission feed 616 to save area on the PCB 608 and avoiding unwanted reflections that can result from a more abrupt transformation from the width  $w_m$  of the microstrip line 614 to the width of the taper region 612 where the taper region 612 joins with the connecting pad 610.

Table II shows the results of a computer simulation run using a standard antenna design simulation software package, as well as the assumed values for various dimensions of an exemplary slotted hat antenna 600 implemented as in FIG. 15. The values for the dimensions of the exemplary slotted hat antenna 600 were obtained through iterative optimization using the software package. A exemplary prototype implementation of the slotted hat antenna 600 of FIG. 15 utilizes FR4® board as the dielectric material for the PCB 608. Some of the exemplary dimensions in Table II relate to a particular mounting system, shown in FIG. 27 and described in more detail below, that was used in which the root 606 of the antenna 600 penetrated the PCB 608 and was soldered to the PCB 608 at the bottom side of the PCB 608.

**Table II**

**Simulation results for an exemplary implementation of the exemplary slotted hat antenna 600 with root 606 of FIG. 15; including dimensions of the exemplary transmission feed 616 of FIGS. 15, 23 and 27, and dimensions of the exemplary mounting system 1200 of FIG. 27.**

<b>Element/Dimension</b>	<b>Value</b>
Operating Frequency	5.25 GHz
Material 600 Thickness $t_h$ , $t_s$ , $t_r$ ; Thickness of Connecting Pad Hole 638 $t_{\text{phole}}$	0.2 mm
Diameter of Hat 602 $d_h$ ; $2r_h$	9 mm
Length of Stem 604 $l_s$ , $\approx$ Height above PCB 608	4.6 mm $[d_h = 2r_h \approx 2l_s; d_h + l_s = 2r_h + l_s \approx \frac{\lambda}{4}]$
Width of Stem 604 $w_s$	1.9 mm
Width of Root 606 $w_r$ ; Width of Connecting Pad Hole 638 $w_{\text{phole}}$	0.815 mm
Length of Root 606 $l_r$	can vary; longer than PCB 608 thickness
Length of Transmission Feed 616	13.6 mm $[l_{\text{feed}} = r_p + l_t + l_m]$
Thickness of Transmission Feed 616	0.07 mm (70 $\mu\text{m}$ )
Impedance of Microstrip Line 614	50 $\Omega$
Width of Microstrip Line 614 $w_m$	0.45 mm

Length of Microstrip Line <b>614</b> $l_m$	5.88 mm
Length of Taper Region <b>612</b> $l_t$	6.52 mm
Diameter of Connecting Pad <b>610</b> $d_p$ ; $2r_p$	2.4 mm
Diameter of Island <b>648</b> $d_i$	2 mm
Diameter of Island Hole <b>654</b> $d_{ihole}$	1 mm
Diameter of Via Hole <b>656</b> $d_{viahole}$	1 mm
Outer Diameter of Moat <b>646</b> (Ground Plane <b>644</b> Gap) $d_m$	2.4 mm
FR4® board (PCB <b>608</b> )	$\epsilon_R \approx 4.25$

FIGS. 31-33 are graphs illustrating performance characteristics relating to input impedance and the bandwidth according to the exemplary implementation of the exemplary slotted hat antenna **600** of FIG. 15. In FIG. 31, the real and imaginary parts of the input impedance, in units of Ohms ( $\Omega$ ), of the antenna **600** on the vertical scale are plotted against frequency, in unit of GHz, on the horizontal scale. At the operating frequency  $f$  of 5.25 GHz, the real part of the input impedance is around 35  $\Omega$ , so that the microstrip line **614** of the transmission feed **616**, which has an impedance of 50  $\Omega$  as shown in Table II, is effectively matched by the antenna **600** in the neighborhood of the operating frequency. In FIG. 32 the bandwidth of the antenna is shown with the magnitude of the voltage standing wave ratio (VSWR) plotted on the vertical scale against frequency on the horizontal scale. The bandwidth for a VSWR less than 3 is around 500 MHz, between 5.0 GHz and 5.5 GHz. FIG. 33 is a magnified portion of the graph in FIG. 32, focused so that the bandwidth for a VSWR less than 2

can more easily be discerned. The bandwidth for  $VSWR < 2$  is around 300 MHz, between 5.1 GHz and 5.4 GHz. In a neighborhood of the operating frequency  $f=5.25$ GHz, the bandwidths are comparable to the bandwidths associated with a traditional top hat antenna, such as the top hat antenna 100 of FIG. 1.

5 Referring now to FIG. 16, it is a diagram illustrating a top view of an exemplary continuous, unitary piece of material 700 used to form an exemplary slotted hat antenna 700 according to a sixth presently preferred embodiment. As will be evident from inspection of FIG. 16, the antenna 700 is similar in nature to the antenna 200 and the description of the antenna 200 with regard to FIGS. 10-12, subject to the following additional commentary, will provide sufficient instruction to one skilled in the art. The exemplary slotted hat antenna 700 differs from the antenna 200 in that the material 700 used to form the antenna 700 includes a stem area or stem 704 that is gradually tapered from a first width  $w_{s1}$  at a dotted line 726 at a center 718 of the a hat area or hat 702 at which the stem 704 is joined with the hat 702, to a second width  $w_{s2}$  at a dotted line 728 at which the stem 704 is joined with a foot area or foot 706. The foot 706 has a width  $w_f$  that, by definition of this embodiment, is preferably less than the width  $w_{s1}$  of the stem 704. and is preferably equal to the width  $w_{s2}$  of the stem 704. Therefore, the width  $w_{s1}$  preferably exceeds the widths  $w_{s2}$  and  $w_f$ . In some embodiments, simulations on exemplary slotted hat antennas mounted on printed circuit boards with a similarly tapered stem showed performance improvements with regard to bandwidth. The tapered stem in a PCB mounting environment exploits the electric field that expands gradually alongside from the base of the tapered stem closest to the PCB to the top of the stem at the hat of the slotted hat antenna.

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In FIG. 17, the unitary piece of material 700 is bent into a shape capable of operating as an antenna. As shown in FIG. 9, preferably the unitary piece of material 700 is bent so that the hat 702 and the stem 704 are perpendicular to one another. Of course, the angle between the hat 702 and the stem 704 is variable and may be adjusted as suitable for performance or mechanical stability reasons, for example. Preferably the unitary piece 700 is bent so that the stem 704 and the foot 706 are perpendicular to one another. Of course, the angle between the stem 704 and the foot 706 is variable and may be adjusted as suitable for performance or mechanical stability reasons, for example.

#### **The Modified Top Hat Antenna**

Referring now to FIG. 18, it is a diagram illustrating a three dimensional view of an exemplary top hat antenna 800, according to a seventh presently preferred embodiment, mounted on a PCB 808. The PCB 808 includes, for example, a substrate such as FR4® board, although other dielectric materials may be used as suitable. FIG. 19 is a diagram illustrating the exemplary top hat antenna 800 of FIG. 18. The exemplary top hat antenna 800 is a modified version of the traditional top hat antenna 100 of FIG. 1. The modified top hat antenna 800 includes a disk or circular hat 802, a cylindrical stem 804, and a cylindrical root 806. The stem 804, the circular hat 802, and the root 806 are distinct pieces that are fused together via any of a series of well-known manufacturing processes to realize the modified top hat antenna 800. In a preferred embodiment, the antenna 800 is made of a metal, such as copper, although any suitable conductive material may be used as suitable.

The dimensional parameters of the antenna 800 include a thickness  $t_h$  of the hat 802, a diameter  $d_h$  of the hat 802, a radius  $r_h$  of the hat 802, a length  $l_s$  of the stem 804, a diameter  $d_s$  of the stem 804, a radius  $r_s$  of the stem 804, a length  $l_r$  of the root 806, a diameter  $d_r$  of the root 806, and a radius  $r_r$  of the root 806. In a preferred embodiment, the radius  $r_s$  of the stem 804 exceeds the radius  $r_r$  of the root 806, although the relative dimensions of the antenna 800 may vary as suitable according to the particular application in which the antenna 800 is used. Preferably, the design dimensions of the antenna 800 are selected in accordance with the environment within which the antenna is intended to operate. For example, in a preferred embodiment, the design dimensions are selected according to an operating frequency, and a corresponding operating wavelength, or corresponding ranges of these, for the antenna 800.

Although selection of the design dimensions is a matter of design choice, as a designer must determine the relative importance of different performance criteria, some rules of thumb may accompany design intuition and numerical modeling of the design dimensions. For example, in a preferred embodiment, the desired length  $l_s$  of the stem 804 of the modified top hat antenna 800 is approximately one-tenth to one-twelfth of the operating wavelength, or from

$\lambda/10$  to  $\lambda/12$ , in the interest of minimizing the height of the antenna 800 above a PCB such as the

PCB 808. Preferably, the height of the antenna 800 above the PCB 808 of FIG. 18 is roughly equivalent to the length  $l_s$  of the stem 804. A design rule of thumb to achieve the length  $l_s$  and to maintain acceptable performance that is comparable to the traditional top hat antenna 100

illustrated in FIG. 1, is to make the radius  $r_h$  of the hat 802 approximately equivalent to the length  $l_s$  of the stem 804 so that (2) and (3) above are satisfied. In a preferred embodiment, the radius  $r_h$  of the hat 802 and the length  $l_s$  of the stem 804 are selected to satisfy (3) and to

minimize  $l_s$ . For example, if the length  $l_s$  is selected to be approximately equal to  $\lambda/12$ , then according to (3) the radius  $r_h$  should be approximately equal to  $\lambda/12$ . As another example, if the length  $l_s$  is selected to be approximately equal to  $\lambda/10$ , then to satisfy (3) the radius  $r_h$  should be approximately equal to  $\lambda/13$ .

5           The antenna 800 of FIG. 19 is capable of being mounted on a PCB, as shown in FIG. 18. The antenna 800 of FIG. 19 is mounted on the PCB 808 and contacts a transmission feed 816 that is laid out along a top side of the PCB 808. FIG. 22 is a diagram illustrating a top view of the exemplary transmission feed 816 of FIG. 18 without the antenna 800. As noted above, the radius  $r_s$  of the stem 804 is preferably longer than the radius  $r_r$  of the root 806 for reasons that will become evident when viewing the antenna 800 of FIG. 18 and when reviewing the description below of mounting systems according to presently preferred embodiments. In FIG. 18, for example, the stem 804 is supported by the transmission feed 816, while the root 804 penetrates the PCB 808 through to a bottom side of the PCB 808. The transmission feed 816 of FIGS. 18 and 22 preferably includes a microstrip line 814, a taper region 812 and a contact area or connecting pad 810. Preferably, the transmission feed 816 is a microthin layer of metal film, such as copper, although other metals and conductive materials may be used as suitable. The connecting pad 810 of FIGS. 15 and 22 is preferably circular having a radius  $r_p$  and diameter  $d_p$  and is joined with the taper region 812. The root 804 and thus the antenna 800 are preferably secured to the PCB 808 by a process that solders or otherwise fuses the root 804 to the bottom of the PCB 808 as explained in more detail below.

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5 The radius  $r_r$  of the root **806** and preferably the radius  $r_s$  of the stem **804** determine the radius  $r_p$  and the diameter  $d_p$  of the connecting pad **810** and the width of the taper region **812** where the taper region **812** joins with the connecting pad **810**. The connecting pad **810** is preferably used to make electrical contact with the root **806** and thus the antenna **800**, and to provide a surface to support the stem **804** and thus the antenna **800**. Preferably, the root **806** penetrates the connecting pad **810** through a pad hole **838** of radius  $r_{\text{phole}}$ . Preferably, the pad hole **838** is shaped to firmly and tightly surround the root **806** to facilitate the electrical contact between the connecting pad **810** and the root **806**. The diameter  $d_{\text{phole}}$  of the pad hole **838** is preferably equivalent to the diameter  $d_r$  of the root **806**. The microstrip line **814**, as is commonly known in the art, is a structure that behaves like a transmission line at microwave frequencies and that transmits electrical signals in conjunction with a dielectric layer and a ground plane, in this case with the PCB **808**. For a given width, such as width  $w_m$ , of microstrip line and a given height of the microstrip line above a ground plane, typically the thickness of the PCB layer, there is an impedance associated with the microstrip line. Preferably, the taper region **812** is used to match the input impedance of the antenna **800** with the microstrip line **814**. The length  $l_t$  of the taper region **812** is dependent on how abrupt a transformation of the microstrip line **814** to the connecting pad **810** is acceptable for a particular application. The tradeoff for this parameter is between reducing the length  $l_{\text{feed}}$  of the transmission feed **816** to save area on the PCB **808** and avoiding unwanted reflections that can result from a more abrupt transformation from the width  $w_m$  of the microstrip line **814** to the width of the taper region **812** where the taper region **812** joins with the connecting pad **810**.

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Table III shows the results of a computer simulation run using a standard antenna design simulation software package, as well as the assumed values for various dimensions of an exemplary top hat antenna 800 implemented as in FIG. 18. The values for the dimensions of the exemplary top hat antenna 800 were obtained through iterative optimization using the software package. A exemplary prototype implementation of the top hat antenna 800 of FIG. 18 utilizes FR4® board as the dielectric material for the PCB 808. Some of the exemplary dimensions in Table III relate to a particular mounting system, shown in FIGS. 25 and 26 and described in more detail below, that was used in which the root 806 of the antenna 800 penetrated the PCB 808 and was soldered to the PCB 808 at the bottom side of the PCB 808.

**Table III**

**Simulation results for an exemplary implementation of the exemplary top hat antenna 800 with root 606 of FIG. 18; including dimensions of the exemplary transmission feed 816 of FIGS. 18, 23, and 25, and dimensions of the exemplary mounting system 1100 of FIGS. 25-26.**

<b>Element/Dimension</b>	<b>Value</b>
Operating Frequency	5.25 GHz
Thickness of Hat 802 $t_h$	0.5 mm
Diameter of Hat 802 $d_h$ ; $2r_h$	11.5 mm
Length of Stem 804 $l_s$ , ~Height above PCB 808	5 mm
	$[d_h = 2r_h \approx 2l_s; d_h + l_s = 2r_h + l_s \approx \frac{\lambda}{4}]$

Diameter of Stem <b>804</b> $d_s$ ; $2r_s$	2 mm
Diameter of Root <b>806</b> $d_r$ ; $2r_r$ ; Diameter of Connecting Pad Hole <b>838</b> $d_{\text{phole}}$	1 mm
Length of Root <b>806</b> $l_r$	can vary; longer than PCB <b>808</b> thickness
Length of Transmission Feed <b>816</b>	12.5 mm $[l_{\text{feed}} \cong d_p + l_i + l_m]$
Thickness of Transmission Feed <b>816</b>	0.07 mm (70 $\mu\text{m}$ )
Impedance of Microstrip Line <b>814</b>	$\sim 53 \Omega$
Width of Microstrip Line <b>814</b> $w_m$	0.4 mm
Length of Microstrip Line <b>814</b> $l_m$	4.5 mm
Length of Taper Region <b>812</b> $l_t$	6 mm
Width of Taper Region <b>812</b> at Connecting Pad <b>810</b>	1 mm
Diameter of Connecting Pad <b>810</b> $d_p$ ; $2r_p$	2 mm
Diameter of Island <b>848</b> $d_i$	2 mm
Diameter of Island Hole <b>854</b> $d_{\text{ihole}}$	1 mm
Diameter of Via Hole <b>856</b> $d_{\text{viahole}}$	1 mm
Outer Diameter of Moat <b>846</b> (Ground Plane <b>844</b> Gap) $d_m$	2.4 mm
Diameter of Relief <b>858</b> in Middle Ground Plane <b>840</b> $d_g$	2 mm

FR4® board (PCB <b>808</b> )	$\epsilon_R \approx 4.25$
Note: In a preferred embodiment, a foam, for example polystyrene, cylinder of height 4.5 mm, diameter $\sim 12$ mm, and having a 2 mm hole along the cylinder axis, could be used for vibration dampening and stem <b>804</b> protection.	

FIGS. 34-37 are graphs illustrating performance characteristics relating to input impedance and the bandwidth according to the exemplary implementation of the exemplary top hat antenna **800** of FIG. 15. In FIG. 34, the real and imaginary parts of the input impedance, in units of Ohms ( $\Omega$ ), of the antenna **800** on the vertical scale are plotted against frequency, in unit of GHz, on the horizontal scale. FIG. 35 is a magnified portion of the graph in FIG. 34, focused so that the real part of the input impedance for the operating frequency can more easily be discerned. At the operating frequency  $f$  of 5.25 GHz, the real part of the input impedance is around 50  $\Omega$ , so that the microstrip line **814** of the transmission feed **816**, which has an impedance of 50  $\Omega$  as shown in Table II, is effectively matched by the antenna **800**. In FIG. 36 the bandwidth of the antenna is shown with the magnitude of the voltage standing wave ratio (VSWR) plotted on the vertical scale against frequency on the horizontal scale. The bandwidth for a VSWR less than 3 is around 1150 MHz, between 4.6 GHz and 5.75 GHz. FIG. 37 is a magnified portion of the graph in FIG. 36, focused so that the bandwidth for a VSWR less than 2 can more easily be discerned. The bandwidth for VSWR  $< 2$  is around 750 MHz, between 4.8 GHz and 5.55 GHz. In a neighborhood of the operating frequency  $f=5.25$ GHz, the bandwidths are comparable to the bandwidths associated with a traditional top hat antenna, such as the top hat antenna **100** of FIG. 1.

### Antenna Mounting Systems

FIG. 25 is a diagram illustrating a side view of an exemplary mounting system 1100, built into the PCB 808 according to an eighth presently preferred embodiment, to mount an exemplary antenna 1000. FIG. 21 is a diagram illustrating an exemplary portion of the exemplary antenna 1000 capable of being mounted on, for example, the PCB 808 in the exemplary mounting system 1100. The antenna 1000 portion includes a cylindrical stem 1004 of radius  $r_s$  and diameter  $d_s$ , and a cylindrical root 1006 of radius  $r_r$  and diameter  $d_r$ . The antenna 1000 is intended to represent any of a wide variety of antennas having this configuration and is consistent with, for example, the exemplary modified top hat antenna 800 of FIGS. 18 and 19. The antenna 1000 can also be, for example, a modified straight wire monopole antenna, or a modified inverted L monopole antenna. The antenna 1000 is configured for insertion into an opening, such as a via hole, in the PCB 808.

The exemplary mounting system 1100 built into the PCB 808 preferably includes the transmission feed 816 of FIGS. 18 and 22, an upper layer 842 of dielectric material, a lower layer 843 of dielectric material, a ground plane 844, and an intermediate ground plane 840 located in between the dielectric material layers 842, 843 so that the ground plane 840 is located on a top side of the lower dielectric layer 843. Although two layers of dielectric material are illustrated, the presently preferred embodiments and methods and systems described herein are not limited to two layers, and any number of layers may be used as suitable. The upper dielectric layer 842 has a top side 860 and is located on a top side of the intermediate ground plane 840. The lower dielectric layer 843 has a bottom side 862. The ground plane 844 is located and laid out along

the bottom side 862 of the lower dielectric layer 843 and the PCB 808. The dielectric material for the layers 842, 843 can be, for example, a dielectric substrate such as FR4® board material, although other dielectric materials may be used as suitable. Preferably, the transmission feed 816 is located and laid out along the top side 860 of the upper dielectric layer 842 and the PCB 808. Preferably, the transmission feed 816 provides the antenna 1000 with electrical signals. Preferably, the transmission feed 816 and the ground planes 840, 844 are microthin layers of metal film, such as copper, although other metals and conductive materials may be used as suitable. An exemplary thickness for the feed 816 and the ground planes 840, 844 is 70 microns (0.07 mm) although any standard thicknesses or other thickness may be used as suitable. As described above, the transmission feed 816 preferably includes a microstrip line 814, a taper region 812, and a contact area or connecting pad 810 to receive and support the antenna 1000. The connecting pad 810 has a diameter  $d_p$  and a radius  $r_p$  while the connecting pad hole 838 has a diameter  $d_{\text{phole}}$  and a radius  $r_{\text{phole}}$ . Although the system 1100 includes an intermediate ground plane 840, in other embodiments, no intermediate ground plane 840 is utilized. Generally, one or more ground planes, or positive DC supply planes, may be used as suitable.

Preferably an opening, for example a via hole 856, is formed through the PCB 808 and the dielectric layers 842, 843. Preferably, the opening is formed by boring or drilling through the PCB 808, with, for example, a drilling tool. Of course, any suitable tool may be used. The opening in the PCB 808 can be formed as a via hole 856 having a diameter  $d_{\text{viahole}}$ . As is known in the art, a via hole is a hole that is bored into a substrate, typically in order to make a shunt connection between two or more conductors. The via hole 856 is preferably a plated through-hole with plating 850 forming the walls of the via hole 856. The PCB 808 and the dielectric

layers **842, 843** are preferably configured to receive the antenna **1000** through the opening. As illustrated in FIG. 25, the antenna **1000** is inserted into the opening on the top side **860** of the upper dielectric layer **842** and the PCB **808**, through the connecting pad hole **838**. Preferably, the cylindrical root **1006** is inserted through the connecting pad **810** into the opening on the top side **860** of the PCB **808**. Preferably, the cylindrical root **1006** makes electrical contact with the transmission feed **816**. Preferably, the connecting pad hole **810** of the transmission feed **816** fully surrounds the cylindrical root **1006** to make electrical contact. Preferably, the connecting pad **810** supports the cylindrical stem **1004**. The step drop in radius from the cylindrical stem **1004** to the cylindrical root **1006** provides mechanical stability for the antenna **1000**. That is, the antenna **1000**, when secured to the bottom of the PCB **808**, will not be permitted to wobble due to the shapes of the connecting pad **810** and the stem **1004** and root **1006** of the antenna **1000**. The stem **1004** preferably rests on the connecting pad **810** while the root **1006** preferably fits snugly into the connecting pad hole **838**, preventing lateral movement of the antenna **1000**.

The system **1100** includes an island **848** having a diameter  $d_i$  and a radius  $r_i$ . The island **848** includes an island hole **854** having a diameter  $d_{ihole}$  and radius  $r_{ihole}$ . Preferably, the island **848** is surrounded and defined by a circular gap area or moat **846** having an outer diameter  $d_m$ . The moat **846** preferably serves the purpose of providing electrical separation between the island **848** and the ground plane **844**, so that the island **848** does not make contact with the ground plane **844**. In a preferred embodiment, the moat **846** is created in the ground plane **844** to form the island **848**. Preferably, the opening is formed through the island **848** along with the PCB **808** including the intermediate ground plane **840**, and the dielectric layers **842, 843** so that the island **848** is configured to receive the antenna **1000** through the opening and the island hole **854**.

Preferably, the moat **846** is formed by etching in a PCB process fabrication step. Process fabrication steps, including etching processes, are well known in the art. Preferably, the middle or intermediate ground plane **840** includes a hole, or relief **858** having a diameter  $d_g$ . Preferably, the opening, the via hole **854**, the relief **858**, the island hole **854**, and the moat **846** are formed together and thus configure the respective elements with which they are associated to receive the antenna **1000**.

Preferably, the root **1006** of the antenna **1006** protrudes through the opening in the island **848** on the bottom side **862** of the PCB **808** once the antenna **1000** is inserted into the via hole **856**. The root **1006** of the antenna **1000** is preferably secured to the PCB **808** at the bottom side of the PCB **808** using a soldering process along the bottom side **862** of the PCB **808**. Of course, any suitable fusing process may be used to fix the antenna **1000** to the PCB **808**.

The island **848** is preferably configured to receive a material **854** to secure the antenna **1000** to the island. The material **854**, for example, soldering metal, is preferably introduced along the bottom side of the PCB **808** over the island **848** and into the via hole **856** if applicable to secure the antenna **1000** to the PCB **808**. Any suitable material **854** may be used; for example, soldering material may be used. In a preferred embodiment, the material **854** is introduced into the via hole **856** to fill any open areas between the antenna **1000** and the opening or via hole **856** via capillary attraction. As is known in the art, capillary attraction pulls the solder up into the opening to fill in any gap between the root **1006** and the plated-through hole, or via hole **856**.

FIG. 26 is a diagram illustrating a bottom view of the exemplary mounting system **1100** of FIG. 25. Preferably, the root **1006** of the antenna **1000** protrudes from the island hole **854** in the island **848**, while the moat **846** separates the island **848** from the ground plane **844**. The

material **852**, such as metal solder, that is used to affix the cylindrical root **1006** of the antenna **1000** to the island **848** and thus to the PCB **808**, is not shown in FIG. 26 for clarity.

FIG. 27 is a diagram illustrating a side view of an exemplary mounting system **1200**, built into the PCB **608** according to a ninth presently preferred embodiment, to mount an exemplary antenna **900**. FIG. 20 is a diagram illustrating an exemplary portion of the exemplary antenna **900** capable of being mounted on, for example, the PCB **608** in a exemplary mounting system **1200**. The antenna **900** portion includes a planar stem **904** of width  $w_s$  and thickness  $t_s$ , and a planar root **906** of width  $w_r$ , length  $l_r$ , and thickness  $t_r$ . The antenna **900** is intended to represent any of a wide variety of antennas having this configuration and is consistent with, for example, the exemplary antenna **300** of FIGS. 5-7 and the exemplary antenna **600** of FIGS. 13-15. The antenna **900** can also be, for example, a modified straight wire monopole antenna, or an modified inverted L monopole antenna. The antenna **900** is configured for insertion into an opening, such as a via hole, in the PCB **608**.

The exemplary mounting system **1200** built into the PCB **608** preferably includes the transmission feed **616** of FIGS. 15 and 23, a layer **642** of dielectric material, and a ground plane **644**. The dielectric layer **642** has a top side **660** and a bottom side **662**. The ground plane **644** is located and laid out along the bottom side **662** of the dielectric layer **642** and the PCB **608**. The dielectric material can be, for example, a dielectric substrate such as FR4® board material, although other dielectric materials may be used as suitable. Preferably, the transmission feed **616** is located and laid out along the top side **660** of the dielectric layer **642** and the PCB **608**. Preferably, the transmission feed **616** provides the antenna **900** with electrical signals. Preferably, the transmission feed **616** and the ground plane **644** are microthin layers of metal

film, such as copper, although other metals and conductive materials may be used as suitable.

An exemplary thickness for the feed **616** and the ground plane **644** is 70 microns (0.07 mm)

although any standard thicknesses or other thickness may be used as suitable. As described

above, the transmission feed **616** preferably includes a microstrip line **814**, a taper region **812**,

5 and a contact area or connecting pad **610** to receive and support the antenna **900**. The connecting

pad **610** has a diameter  $d_p$  and a radius  $r_p$  while the connecting pad hole **638** has a diameter  $d_{phole}$

and a radius  $r_{phole}$ . Although the system **1200** includes one ground plane **644**, in other

embodiments such as in the system **1100** of FIGS. 25-26, more than one ground plane is utilized.

Generally, one or more of ground planes may be used as suitable.

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Preferably an opening, for example a via hole **656**, is formed through the PCB **608** and the dielectric layer **642**. Preferably, the opening is formed by boring or drilling through the PCB **608**, with, for example, a drilling tool. Of course, any suitable tool may be used. The opening in the PCB **608** can be formed as a via hole **656** having a diameter  $d_{viahole}$ . As is known in the art, a via hole is a hole that is bored into a substrate, typically in order to make a shunt connection between two or more conductors. The via hole **656** is preferably a plated through-hole with plating **650** forming the walls of the via hole **656**. The PCB **608** and the dielectric layer **642** are preferably configured to receive the antenna **900** through the opening. As illustrated in FIG. 25, the antenna **900** is inserted into the opening on the top side **660** of the dielectric layer **642** and the PCB **608**, through the connecting pad hole **638**. Preferably, the planar root **906** is inserted through the connecting pad **610** into the opening on the top side **660** of the PCB **608**. Preferably, the planar root **906** makes electrical contact with the transmission feed **616**. Preferably, the connecting pad hole **610** of the transmission feed **616** fully surrounds the planar root **906** to make

electrical contact. Preferably, the connecting pad 610 supports the planar stem 904. The step drop in width from the planar stem 904 to the planar root 906 provides mechanical stability for the antenna 900. That is, the antenna 900, when secured to the bottom of the PCB 608, will not be permitted to wobble due to the shapes of the connecting pad 610 and the stem 904 and root 906 of the antenna 900. The stem 904 preferably rests on the connecting pad 610 while the root 906 preferably fits snugly into the connecting pad hole 638, preventing lateral movement of the antenna 900.

The system 1200 includes an island 648 having a diameter  $d_i$  and a radius  $r_i$ . The island 648 includes an island hole 654 having a diameter  $d_{ihole}$  and radius  $r_{ihole}$ . Preferably, the island 648 is surrounded and defined by a circular gap area or moat 646 having an outer diameter  $d_m$ . The moat 646 preferably serves the purpose of providing electrical separation between the island 648 and the ground plane 644, so that the island 648 does not make contact with the ground plane 644. In a preferred embodiment, the moat 646 is created in the ground plane 644 to form the island 648. Preferably, the opening is formed through the island 648 along with the PCB 608 and the dielectric layer 642 so that the island 648 is configured to receive the antenna 900 through the opening and the island hole 654. Preferably, the moat 646 is formed by etching in a PCB process fabrication step. Process fabrication steps, including etching processes, are well known in the art. Preferably, the opening or via hole 656, the island hole 654, and the moat 646 are formed together and thus configure the respective elements with which they are associated to receive the antenna 900.

Preferably, the root 906 of the antenna 906 protrudes through the opening in the island 648 on the bottom side 662 of the PCB 608 once the antenna 900 is inserted into the via hole

656. The root 906 of the antenna 900 is preferably secured to the PCB 608 at the bottom side of the PCB 608 using a soldering process along the bottom side 662 of the PCB 608. Of course, any suitable fusing process may be used to fix the antenna 900 to the PCB 608.

The island 648 is preferably configured to receive a material 652 to secure the antenna 900 to the island. The material 652, for example, soldering metal, is preferably introduced along the bottom side of the PCB 608 over the island 648 and into the via hole 656 if applicable to secure the antenna 900 to the PCB 608. Any suitable material 652 may be used; for example, soldering material may be used. In a preferred embodiment, the material 652 is introduced into the via hole 656 to fill any open areas between the antenna 900 and the opening or via hole 656 via capillary attraction. As is known in the art, capillary attraction pulls the solder up into the opening to fill in any gap between the root 906 and the plated-through hole, or via hole 656.

Preferably, the design dimensions of the antennas 1000, 900 and the mounting systems 1100, 1200 are selected in accordance with the operating frequency and the environment within which the antenna is intended to operate. For example, in a preferred embodiment, the design dimensions are selected according to an operating frequency, and a corresponding operating wavelength, or corresponding ranges of these, for the antennas 1000, 900.

Although selection of the design dimensions is a matter of design choice, as a designer must determine the relative importance of different performance criteria, some rules of thumb may accompany design intuition and numerical modeling of the design dimensions. For

antennas that include a circular hat and a stem, the design rule of thumb to achieve the length  $l_s$

of around  $\lambda/12$  to  $\lambda/10$  and to maintain acceptable performance that is comparable to the

traditional top hat antenna 100 illustrated in FIG. 1, is to make the radius  $r_h$  of the antenna hat

approximately equivalent to the length  $l_s$  of the stem as in (2) and (3). This rule may apply to the antennas 1000, 900, depending on the type of antenna that is used.

Definitions as well as rules of thumb to achieve desired performance may be formulated as well for the design dimensions of the mounting system 1100 (1200) of FIGS. 25-26 (FIG. 27).

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- By definition, and referring to FIGS. 25-26 (FIG. 27):

$$d_m > d_i > d_{ihole}, \quad (4)$$

that is, the outer diameter  $d_m$  of the moat 846 (646) exceeds the diameter  $d_i$  of the island 848 (648), while the island 848 (648) exceeds the diameter  $d_{ihole}$  of the island hole 854 (654).

- Preferably, the diameters of the holes related to the opening that receive the antenna 1000 (900) are approximately equivalent:

$$d_{ihole} \cong d_{viahole}, \quad (5)$$

that is, the diameter  $d_{ihole}$  of the island hole 854 (654), and the diameter of the via hole 856 (656)

15 are preferably equivalent to each other. Of course, these dimensions may vary in practice according to processes but are preferably designed to be equivalent.

- Generally, the diameter  $d_{phole}$  (width  $w_{phole}$ ) of the connecting pad hole 838 (638) is greater than or equal to the diameter  $d_r$  (width  $w_r$ ) of the cylindrical (planar) root 1006 (906):

$$20 \quad d_{phole} \geq d_r \quad (w_{phole} \geq w_r). \quad (6)$$

Since the connecting pad hole **838 (638)** preferably fully surrounds the cylindrical (planar) root **1006 (906)** in order to achieve electrical contact between the transmission feed **816 (616)** and the cylindrical (planar) root **1006 (906)**, then preferably the diameter  $d_{\text{phole}}$  (width  $w_{\text{phole}}$ ) of the connecting pad hole **838 (638)** is approximately equivalent to the diameter  $d_r$  (width  $w_r$ ) of the cylindrical (planar) root **1006 (906)**:

$$d_{\text{phole}} \cong d_r \quad (w_{\text{phole}} \cong w_r). \quad (7)$$

- Preferably, the diameter  $d_s$  (width  $w_s$ ) of the cylindrical (planar) stem **1004 (904)** exceeds the diameter  $d_r$  (width  $w_r$ ) of the cylindrical (planar) root **1006 (906)**:

$$d_s \geq d_r \quad (w_s \geq w_r), \quad (8)$$

and by definition and by (6):

$$d_p > d_{\text{phole}} \geq d_r \quad (d_p > w_{\text{phole}} \geq w_r), \quad (9)$$

that is, the diameter  $d_{\text{phole}}$  (width  $w_{\text{phole}}$ ) of the connecting pad hole **838 (638)** is less than the diameter  $d_p$  of the connecting pad **810 (610)** and is greater than or equal to the diameter  $d_r$  ( $w_r$ ) of the cylindrical (planar) root **1006 (906)**. Preferably, for support of the stem **1004 (904)**, the diameter  $d_p$  of the connecting pad **810 (610)** exceeds the diameter  $d_s$  ( $w_s$ ) of the stem **1004 (904)**:

$$d_p > d_s \quad (d_p > w_s), \quad (10)$$

so that preferably, and by (7):

$$d_p > d_s > d_{\text{phole}} \cong d_r \quad (d_p > w_s > w_{\text{phole}} \cong w_r), \quad (11)$$

with solder or another material preferably filling in any open areas between the cylindrical (planar) root **1006 (906)** and the via hole **856 (656)**.

The following relationships between design dimensions are preferable for optimum performance of the antenna 1000 (900) in the mounting system 1100 (1200) with regard to bandwidth, and input and output impedance, although of course any suitable dimensions may be used.

- Preferably, the diameter  $d_i$  of the island 848 (648) is greater than the diameter  $d_r$  ( $w_r$ ) of the cylindrical (planar) root 1006 (906):

$$d_i > d_r \quad (d_i > w_r). \quad (12)$$

As the diameter  $d_i$  of the island 848 (648) increases relative to the diameter  $d_r$  ( $w_r$ ) of the cylindrical (planar) root 1006 (906) the output impedance of the antenna decreases.

- Preferably, the diameter  $d_g$  of the relief 858 in the intermediate ground plane 840 and the outer diameter  $d_m$  of the gap area or moat 846 (646) are, respectively, greater than or equal to the diameter  $d_p$  of the connecting pad 838 (638) as follows:

$$d_g \geq d_p, \quad (13)$$

and

$$d_m \geq d_p \quad (d_m \geq d_p). \quad (14)$$

As used herein, the term transmission feed is intended to refer to a feed structure that may include a transmission line structure as well as a contact area or connecting pad. The transmission line structure may include a distributed element such as a microstrip line, or for example, a stripline. As is known in the art, a stripline is a strip of metal, for example, copper, sandwiched between two ground planes and a dielectric material. The transmission line structure may be any suitable implementation that may be modeled as a transmission line.

As used herein, the term bendable is intended broadly to refer to any configuration or state of affairs that allows bending to occur. For example, a material may be thin enough or pliant enough to bend. Any such material is thus bendable. As another example, a material may contain an impression or a ridge along a desired bending line that aids in bending the material. Any such material is thus bendable.

The antennas and mounting system described herein according to the presently preferred embodiments satisfy performance requirements with regard to impedance and bandwidth and minimize the corresponding area required on a PCB while reducing the costs associated with the manufacturing, mounting, and soldering processes. The antennas and mounting systems may be designed to operate according to a wide variety of frequencies and in a wide range of environments.

Although the present invention has been particularly described with reference to the preferred embodiments, it should be readily apparent to those of ordinary skill in the art that changes and modifications in the form and details may be made without departing from the spirit and scope of the invention. It is intended that the appended claims include such changes and modifications.